Preliminary Results from the Coupled Atmosphere-Ocean Regional Climate Model at the Meteorological Research Institute

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Abstract

A ten-year integration of the Meteorological Research Institute Coupled atmosphere-ocean Regional Climate Model (MRI-CRCM) was conducted to evaluate the model’s performance in reproducing the present climate around Japan (CRCM run). MRI-CRCM couples a 20 km-mesh atmosphere Regional Climate Model (RCM20), and a North Pacific Ocean General Circulation Model, whose horizontal resolution is 1/4° (longitude) × 1/6° (latitude). Multi-nesting method is used for calculating the atmospheric part. A 60 km-mesh atmosphere Regional Climate Model (RCM60) is nested in MRI Coupled General Circulation Model, and RCM20 is nested in RCM60. To verify the effect of coupling, an atmospheric RCM run, that specified SST from a global coupled model run, was also conducted (ARCM run). Compared with observations, sea surface temperatures (SSTs) are overestimated in both runs for the winter over the Japan Sea. In the CRCM run, the SST simulation is somewhat improved and surface air temperature (1.5 m above the ground) is also lower than in the ARCM run.

Japan is classified into seven regions according to climatic features. Compared with observational data, summer surface air temperatures in both runs are somewhat high in most of Japan, except for southern regions. This warm bias is reduced in the CRCM run as compared to the ARCM. The improvements in the CRCM run are especially large in northern Japan, where the differences between the runs exceed 1.5 K. The precipitation simulations are compared with radar-AMeDAS data. A typical winter pattern with much rainfall along the coast of the Japan Sea, compared to the coast of the Pacific Ocean, are well reproduced in both runs, but the simulated precipitation is overestimated on the Pacific coast in winter. Precipitation is generally overestimated in northern Japan, while underestimated in western Japan throughout the year. Precipitation is less in the CRCM than in the ARCM run, because of the reduced latent heat flux and lower SSTs. The MRI-CRCM is an effective means to reproduce the Japanese climate, but has still biases in temperature and precipitation. Further improvements are needed.

1. Introduction

High-resolution climate projection is becoming an important issue for obtaining detailed information about climate change due to global warming. Coupled atmosphere-ocean general circulation models (CGCM) are usually used for global climate change studies. However, horizontal resolutions of those models are generally just a few degrees, and cannot fully express climate change in detail over Japan. Dickinson et al. (1989) and Giorgi and Bates (1989) started numerical simulations of regional climate models (RCMs). Those models included the treatment of land surface processes, such as Biosphere-Atmosphere Transfer Scheme (BATS, Dickinson et al. 1993), and Land Surface Model (LSM, Bonan 1995). Mabuchi et al. (2000, 2002) carried out numerical
simulations on regional climate over Japan, and regional CO₂ circulation. Their model treated the land-surface processes called Biosphere-Atmosphere Interaction Model (BAIM). As stated above, some numerical simulations are sophisticated in their treatment of land-surface processes. However, SST is given as an external parameter that is calculated separately from the RCMs, and very little effort has been made for precisely treating the flux from sea surface in RCMs. The atmosphere and ocean are closely interrelated through fluxes of heat and moisture at the sea surface. The interaction between atmosphere and ocean needs to be included in RCMs in a more sophisticated way, especially to properly reproduce climate over Japan, which is surrounded by the sea.

The complex situation of the ocean around Japan, such as ocean currents and land-sea distribution are depicted in Fig. 1. Four ocean currents flow and some of them collide into each other around Japan. The Kuroshio flows along the southern coastline of the Japanese Islands, and flows away to the east from Japan at the eastern edge of Honshu. The point of separation changes every year, and the flow often meanders widely. The Kuroshio carries warm water from low latitude, releasing a large quantity of heat and moisture into the atmosphere. A cold ocean current, called the Oyashio, flows from the north. The cold wind blows over the Oyashio, and often creates serious crop damage in northern Japan in early summer. This phenomenon is called Yamase. Ninomiya and Mizuno (1985) pointed out that the cold air was somewhat modified by the Pacific Ocean around Japan, and low-level clouds were formed due to the modification. A warm ocean current, called the Tsushima Warm Current, and a cold current, called the Liman Current, flow into the Japan Sea from south and north, respectively. The cold, dry air blowing from the Asian Continent is modified by the heat and moisture fluxes from the Japan Sea, resulting in heavy snowfall along the coastal region facing the Japan Sea in winter. In this way, these ocean currents seriously affect the Japanese climate. Hence it is necessary for precise expression of the Japanese climate to reproduce these ocean currents as accurately as possible.

We developed the Meteorological Research Institute-Coupled atmosphere-ocean Regional Climate Model (MRI-CRCM), to reproduce and project climate change more precisely. Another goal of MRI-CRCM is to project climate change of the ocean around Japan. Change of SST, sea-level height, flow pattern of the Kuroshio, and vertical profiles of temperature and salinity are of serious concern to industry, and decision makers in politics.

In this study, a high-resolution ocean model, and an atmosphere model are coupled. The high-resolution ocean model, whose horizontal resolution is 1/4° (longitude) × 1/6° (latitude), is used for the oceanic component of MRI-CRCM. This resolution is not fine enough to express the separation of the Kuroshio and ocean fronts perfectly, but the lower limit to express them. However, we cannot use a finer resolution model because of limitations of computational resources. For the atmospheric component, MRI-RCM (20 km resolution) is used. The performance of the previous version of MRI-RCM has been verified by nesting MRI-RCM in the global analysis data around Japan (Sasaki et al. 1995; Mabuchi et al. 2000; Sasaki et al. 2000; Mabuchi et al. 2002). To demonstrate the accuracy of MRI-CRCM, we performed ten-year integrations of MRI-CRCM driven by MRI-CGCM. The reproducibility of the present climate was investigated by comparing the calculated results with observational data to evaluate the performance of MRI-CRCM.
This paper is organized as follows. Section 2 presents the model structure and briefly describes the experimental way. Section 3 presents the results of numerical experiments. Section 4 presents the summary and concluding remarks.

2. Model description and experimental design

2.1 MRI coupled atmosphere-ocean regional climate model (MRI-CRCM)

MRI-CRCM couples a 20 km-mesh atmosphere Regional Climate Model (RCM20) and a North Pacific Ocean General Circulation Model (NPOGCM, Tsujino and Yasuda 2004). Outside RCM20, NPOGCM is driven by the data of a 60 km-mesh RCM (RCM60) and the second version of MRI Coupled General Circulation Model (MRI-CGCM2.2; an update version of the MRI-CGCM2, Yukimoto et al. 2001), which are calculated separately before MRI-CRCM integration starts. Figure 2 shows the calculation domains of the atmospheric component and the ocean component of MRI-CRCM. MRI-CRCM consists of two models: NPOGCM and RCM20. Since the region of RCM20 is smaller than that of NPOGCM, calculated results of two other models (MRI-CGCM2.2 and RCM60) are necessary for driving NPOGCM. Each model component will be briefly described in the following subsections. The arrows in the figure express the direction of the data flows between the components. A dotted arrow indicates the flow of SST data calculated by NPOGCM. The SST calculated by NPOGCM is used for the lower boundary condition of RCM20, and the atmospheric surface data calculated by RCM20 drives NPOGCM. Therefore, RCM20 and NPOGCM couple each other, as the data are transferred in two ways between them. The variable transferred from NPOGCM to RCM20 is SST data. The variables transferred from RCM20 to NPOGCM are sea-level pressure, surface wind, surface temperature, surface specific humidity, precipitation amount, downward shortwave and downward longwave radiative fluxes. NPOGCM calculates surface fluxes using these atmospheric data. Outside of the domain of RCM20, NPOGCM is driven by the atmospheric data of RCM60 and MRI-CGCM2.2. The SST of RCM60 is supplied by MRI-CGCM2.2. Multi-nesting method is used for calculating the atmospheric part. RCM60, which covers the Asian region, is nested in MRI-CGCM2.2, and RCM20 is nested in RCM60.

2.2 MRI-CGCM2.2

MRI-CGCM2.2 was developed at MRI to investigate climate change associated with forcing due to human activity. This model is a modified version of MRI-CGCM1 (Tokioka et al. 1996) to reproduce a more realistic climate. Horizontal resolution of the atmospheric component is T42 (2.8° × 2.8°). There are 30 layers in the vertical direction. A three-layer Simple Biosphere model (SiB) is used for the land-surface process. The horizontal resolution of
the oceanic component is 2.5° in longitude and 0.5° to 2° in latitude, and there are 23 vertical layers. Further information about the model is provided in Yukimoto et al. (2001).

2.3 NPOGCM

NPOGCM was developed at MRI to express the fine structure of the North Pacific Ocean. The model uses the primitive equation with the hydrostatic and Boussinesq approximation. The model covers the North Pacific Ocean spanning from 15°S to 65°N in latitude, and from 100°E to 75°W in longitude. The Indonesian passage and the Bering Strait are closed. Temperature and salinity are restored to the climatology at the southern boundary of the model. Its horizontal resolution is 1/4° in longitude and 1/6° in latitude. There are 48 vertical layers with thickness increasing from 3 m at the surface to 250 m in the deep layer. The level 2.5 turbulent closure scheme of Mellor and Yamada (1982) is used for the vertical viscosity and diffusivity. Further details of the model are shown in Tsujino and Yasuda (2004).

2.4 MRI-RCM (RCM20 and RCM60)

RCM20 is used for reproducing the climate in the Japanese region. RCM20 was developed based on the Regional Spectral Model (RSM). The Japan Meteorological Agency (JMA) has been using RSM operationally for short-term weather forecasts for East Asia since 1996. RCM20 uses a Lambert conformal projection and its transform grid interval is 20 km at 30°N and 60°N. We adopt 129 × 129 for the grid number to cover almost all of Japan, except some of the Nansei Islands. There are 36 vertical layers. Hybrid coordinates are adopted for the vertical direction. Specifically, σ-coordinates are used for the lower layers and P-coordinates for the upper layers. The precipitation process includes large-scale condensation and evaporation of raindrops. Both the Arakawa-Schubert, and the moist convective adjustment schemes are used for the parameterization of convection. More detail of the RSM is shown in the report by Numerical Prediction Division/JMA (1997).

RCM, which was developed for short-term forecasts, was converted into a climate model that could be used for long-term integration. The two main modifications are introduced briefly here. One is a land process. Ground temperature is solved by the heat conduction equations. The original RSM has four layers in 0.6 m depth for the land process, while MRI-RCM has six layers in 2 m depth in order that the change of temperature is small enough at the lowest level. RCM20 predicts soil moisture and snow depth, while the prediction processes are not included in RSM.

The other major modification is that RCM20 uses the Spectral Boundary Coupling (SBC, Kida et al. 1991) method developed at MRI. The SBC method is implemented as follows. The results of an outer model and an inner model are individually expanded in a two-dimensional Fourier series. The spectra are divided into a long-wave part and a short-wave part at a specified spectral wave number in the outer and inner models. The long-wave part of the outer model, and the short-wave part of the inner model, are coupled. The coupled fields are used for the new fields of the inner model. This method is applied at a certain interval. More details of the SBC method are shown in Kida et al. (1991), Sasaki et al. (1995) and Sasaki et al. (2000).

RCM60 has the same structure as RCM20, except for horizontal resolution and grid number. RCM60 uses a grid interval of 60 km, and grid number of 173 × 129. The calculation domain includes the Tibetan Plateau, which is supposed to affect the Japanese climate.

2.5 Experimental design

In this study, the coupled run by MRI-CRCCM was conducted for 10 years (1991 to 2000). Here after we call this type CRCM run. To verify the effect of coupling, an atmospheric RCM run, that specified SST as an external parameter, was also conducted. Here after, we call this type ARCM run. In the ARCM run, SST was calculated as follows. First, NPOGCM was driven by the monthly mean of atmospheric fields of MRI-CGCM2.2 for the whole domain from 1981 to 2000. The SST calculated by NPOGCM separately from RCM20 was used as the lower boundary condition of RCM20. The other processes are the same as the CRCM run.
Fig. 3. SST distribution of the CRCM run (left panels), the ARCM run (middle panels), and analysis of the JMA (right panels). The SST is averaged over three months, from December to February (DJF), from March to May (MAM), from June to August (JJA), and from September to November (SON).
To calculate boundary conditions for RCM20, the time integration of the RCM60 started from 1 September 1990 with the SST data of MRI-CGCM2.2. In both runs, the time integrations of RCM20 started from 1 October 1990, and the results of integrations of the first three months were discarded from analyses of the results by regarding as the period of spinning up of the models.

3. Results

3.1 SST

The left column panels in Fig. 3 depict seasonal SSTs, averaged for the 10 years, reproduced by the CRCM run. The middle column panels show the SST used in the ARCM run. The right column panels present analyzed SST produced by the JMA once a month. The resolution of the analysis data is 0.25° in both latitude and longitude. The 10-year mean (from 1994 to 2003) of the analysis data is compared with the calculated SSTs. The analysis shows that the cold SST penetrates to the south along the eastern coastal line of the Asian Continent, due to the Liman cold current in the Japan Sea. Warm SST penetrates to the north along the western coast of the Japanese Islands, due to the Tsushima warm current. These different ocean currents form the structure of SST in the Japan Sea. In short, SST is cold in the western area of the Japan Sea, and warm in the eastern area of the Japan Sea. The contrast between the east and west is not reproduced in the ARCM run. The SST at the western area is even higher than the other part. On the other hand, in the CRCM run, SST is colder in the western part of the Japan Sea and warmer along the western coast of the Japanese Islands. The improvement in the CRCM run is due to NPOGCM using high-resolution atmospheric data, which includes detailed information of land-sea distribution and orography. In contrast, NPOGCM is driven by atmospheric data, with only the large-scale information in the ARCM run. Some problems are also seen in the figure. In winter, analysis data indicates low SST, less than 4 K, in the northwestern area of the Japan Sea. This low SST cannot be reproduced in the ARCM run, and this SST difference between the analysis and the ARCM run reaches about 9 K. The CRCM run reduces the error by 1–2 K, but the error is still serious.

Also, analysis shows that there is a front around 40°N in the Japan Sea in winter. However, neither run could express this front, and the temperature gradient is small compared to the analysis. We should resolve the problems and improve the model further.

Figure 4 depicts the root mean square error (RMSE) and bias in each month. Both scores are calculated over the sea in the calculation domain of RCM20. The biases indicate that both runs overestimate SST in winter, and underestimate it in summer. The SST of the CRCM run is lower than that of the ARCM run for all months. RMSE indicates that the SST of the CRCM run is better than that of the ARCM run in winter and spring, and worse in summer and autumn. This systematic annual change of the RMSE reflects the bias characteristic of the two runs mentioned above. The annual mean
bias of the CRCM run is nearly zero, whereas, that of the ARCM run is \(+0.8\) K. The annual mean RMSE of the CRCM run is also smaller than that of the ARCM run. The annual means of the scores demonstrate that the CRCM run is totally better overall than the ARCM run.

Fig. 5. Surface air temperature of the CRCM run (left panels), and the ARCM run (right panels).
### 3.2 Surface air temperature

Figure 5 depicts the mean surface air temperature at 1.5 m above the sea or land surface. Similar to the SST, the temperature over the sea, reproduced by the CRCM run, is lower than that by the ARCM run. This clearly reflects the difference of SST between the runs. Over land, little difference can be seen between the two runs. However, areas below 0°C of the CRCM run spread more widely than those of the ARCM run around the central mountain range of Honshu (the main island of Japan) in winter. Some of the difference is induced by the different SSTs used in the two runs. The effect of SST on surface air temperature must be evaluated to demonstrate the importance of the CRCM for climate projection. In this subsection, we focus on how the different SSTs affect the surface air temperature over land.

The surface air temperatures calculated from both runs are compared with the observation to quantitatively investigate their reproducibility. We divide Japan into seven regions, as illustrated in Fig. 6, according to regional climate features. The surface air temperatures of the models are compared with the observational data of observation stations over land in each region. The elevation of the model topography in Japan averages 400 m higher than that of observation points, accordingly both runs and observed temperatures are adjusted to the mean sea level, assuming that the lapse rate is 0.006 K/m. The grid point values over the sea are excluded in this analysis.

Figure 7 presents the monthly mean surface air temperatures of the observation and the CRCM run, as well as biases of the CRCM run and ARCM run from observations in each region. Both runs accurately reproduce the seasonal change in temperature. However, the surface temperatures in almost all regions are overestimated, except from April to June in regions 4–7. The biases demonstrate that the temperature of the CRCM run is generally lower than that of the ARCM run, and this temperature difference exceeds 1.5 K in region 3 in winter. SST is the only different condition used in the two runs. It is inferred that the SST difference causes the difference of surface air temperature over land.

As stated in 3.1, SSTs of both runs are overestimated in the northern Japan Sea in winter. If the NPOGCM can express the SST in the Japan Sea more accurately, RCM20 may be able to reproduce the surface temperature more closely to the observed temperature. Thus, an additional experiment, with the following condition, was conducted. First, the daily anomaly from the 10-year average is calculated from the SST, produced by NPOGCM, driven by the meteorological field of MRI-CGCM2.2. The new SST field is generated by adding this anomaly to the 10-year average of the analysis SST data described in 3.1. With this modification, the 10-year average of the SST is the same as analysis data, and the daily fluctuation is the same as the SST calculated by NPOGCM. Another 10-year integration of RCM20 was performed, using such SST (EXP.SST). Figure 8 displays bias calculated in this experiment in regions 1, 2 and 3, where the bias of surface air temperature is large. The reproducibility of surface air temperature in winter is improved in EXP.SST, but that in summer changed little,
suggesting that the SST seriously affects the air temperature in winter. During winter, the lower atmosphere layer is unstable, and the air mass is modified by the ample supply of heat and moisture from the sea. However, during summer, the effect of SST is comparatively

Fig. 7. Line graph plotting the surface air temperature of observation and the CRCM run. The bar graph indicates the bias of the CRCM and the ARCM runs from the observation. ① The Japan Sea side of Northern Japan, ② The Pacific Ocean side of Northern Japan, ③ The Japan Sea side of Eastern Japan, ④ The Pacific Ocean side of Eastern Japan, ⑤ The Japan Sea side of Western Japan, ⑥ The Pacific Ocean side of Western Japan, ⑦ The Nansei Islands.
small, as the atmosphere in the lower layer is stable over the sea. Because of this, the reproducibility of the surface air temperature in winter becomes better, if the expression of the SST in the Japan Sea is improved. However, there are other possible reasons for the overestimation of the surface air temperature in summer. The effects of the high pressure located over the Okhotsk Sea, which brings cool air to northern Japan, may not be taken well represented in the boundary condition, or the land-surface process may not be fully accurate. Further investigation is needed to understand the reason of warm bias in summer.

3.3 Precipitation

In this study, the radar-AMeDAS (Automated Meteorological Data Acquisition System) precipitation is used for verifying the models' precipitation amounts. The radar-AMeDAS data precipitation over Japan is calculated using the meteorological radar data, and AMeDAS observational data in the JMA. Its horizontal resolution is $0.05^\circ$ in latitude and $0.0625^\circ$ in longitude, or about 5 km. There is no data on the sea far from the coast, in areas where the radar beam cannot reach, and reliability becomes worse as distance from the radar site increases. Data is available only for the sea near the coast, and on land. The monthly mean data is produced by using the hourly data from 1995 to 2000. The data of 5 km resolution is available only during this period. The precipitation patterns of the CRCM, and ARCM runs are almost the same, thus Fig. 9 presents only the precipitation distribution of the CRCM run, and radar-AMeDAS.

During winter around Japan, the northwesterly monsoon wind generally blows from the Asian Continent to Japan. The monsoonal air, which is cold and dry, is modified from below, through an ample supply of heat and water vapor, during its flow over the Japan Sea. There is much precipitation on the coast of the Japan Sea side. The air mass that has passed over the backbone mountain range becomes very dry. There is less precipitation on the coast of the Pacific Ocean side. The Japanese climate exhibits a distinct contrast between the coastal area of the Japan Sea side, and the Pacific Ocean side in winter, even though the distance between them is only a few hundred kilometers. The precipitation of the CRCM run accurately reproduces this characteristic, which can be distinctly seen in the radar-AMeDAS data. However, the precipitation amount of the CRCM run exceeds the radar-AMeDAS precipitation amount along the Pacific Ocean coast, as the model expresses that the storm track over the sea is too close to the Japanese Islands.

The precipitations of the CRCM and the ARCM runs are statistically verified to quantitatively investigate it. Figure 10 also demonstrates that the precipitation in the coastal
Fig. 9. Precipitation distribution of the CRCM run (left panels), and Rader-AMeDAS (right panels).
Fig. 10. Monthly mean precipitation of the radar-AMeDAS, the CRCM run and the ARCM run. The bottom right panel shows the precipitation difference from the radar-AMeDAS observation. ① The Japan Sea side of Northern Japan, ② The Pacific Ocean side of Northern Japan, ③ The Japan Sea side of Eastern Japan, ④ The Pacific Ocean side of Eastern Japan, ⑤ The Japan Sea side of Western Japan, ⑥ The Pacific Ocean side of Western Japan, ⑦ The Nansei Islands.
area of the Japan Sea (regions (1), (3), and (5)) exceeds that in the coastal area of the Pacific Ocean (regions (2), (4), and (6)) in winter. As mentioned for Fig. 9, the precipitation of the CRCM run exceeds that of the observation in the coastal area of the Pacific Ocean. However, in the CRCM run, the precipitation is closer to the observation than in the ARCM run in winter.

Reproduction of precipitation in the warm season is also important for RCMs. From June to September, observation by radar-AMeDAS suggested that a large amount of precipitation exists in eastern and western Japan, and the Nansei Islands. During the rainy season in June and July, the Baiu front stays along the southern coastal line of Japan. In September, another stationary front is also often seen along the southern coast of Japan. Tropical cyclones are an important factor affecting precipitation for the period. They move along the rim of the subtropical high, and often interact with the stationary front. Those large-scale conditions create a large amount of precipitation, due to strong advection of water vapor from the western or southern direction, especially to west Japan (the right panel of JJA in Fig. 9). The large precipitation amounts are not reproduced sufficiently for the region of west Japan in either run. This situation is illustrated in the left panel of JJA in Fig. 9, and also in regions (5) and (6) of Fig. 10. This may be because small-scale intense rain storms often occur, and induce a disastrous amount of precipitation, concentrated in very small areas in west Japan (see the panels of JJA in Fig. 9). These small-scale rain storms may not be reproduced by the 20 km resolution model. Furthermore, strong water vapor flow to west Japan can create large amounts of rain, with upward motions forced by orography. The orographic effect may not be expressed by the model in detail. These may be the reasons for the dry bias of both models. Comparing the results of both models, the precipitation amount of the CRCM run is almost always smaller than that of the ARCM run, because of cooler SST. During the warm period, the CRCM run shows somewhat lower scores, due to the smaller amounts of precipitation than those in the ARCM run. However, in the north and east regions, precipitation amounts are accurately reproduced by the models. For these regions (1), (2), (3) and (4), the CRCM run shows improvements over the ARCM run.

The precipitation amount averaged over all regions of the CRCM run is improved, compared with the ARCM run for many months. The annual average bias of the CRCM run is \( -5 \) mm, and that for the ARCM run is \( +15 \) mm. Therefore, precipitation amounts averaged over all regions, are somewhat underestimated in the CRCM run, and overestimated in the ARCM run. This is because the SST of the ARCM run is warmer than that of the CRCM run, thus the latent heat transferred from the sea of the ARCM run is also larger than that of the CRCM one.

4. Summary and concluding remarks

A Coupled atmosphere-ocean Regional Climate Model (MRI-CRCM) was developed at MRI. MRI-CRCM couples the high-resolution atmospheric model and the high-resolution ocean model. MRI-CRCM can introduce the interaction between the atmosphere and ocean into climate simulations in a sophisticated manner. Moreover, the model can reproduce and project the detailed structure of the ocean around Japan. MRI-CRCM improves reproduction of the structure of SST over the Japan Sea, where the ARCM run exhibits a large warm bias of SST in winter. However, SST scores become worse in the CRCM run than in the ARCM run in summer. All the year round, SST reproduced by the CRCM run is lower than SST reproduced by NPOGCM, without interaction with RCM20. For annual mean scores of SST, the CRCM run produces better results than the ARCM run. Surface air temperature is investigated over the Japanese Islands. Surface air temperature of the ARCM run has a large warm bias in Northern Japan. The CRCM run reduces the warm bias, especially in winter. An additional experiment, conducted by using the SST, which is adjusted to the analysis SST, demonstrates that the warm bias of surface air temperature in winter is due to the warm bias of the SST. However, the warm bias in summer is not due to the SST, but to other reasons. One possible reason for the warm bias in summer is that a high pressure often develops over the Sea of Okhotsk, and the cold air blows from there in this season. The model may not be
able to express the effect of the high pressure through the lateral boundary. This experiment shows that the progress of the SST expression will improve the reproducibility of the surface air temperature in winter. However, the reproducibility in summer will not be improved.

The calculated precipitation is compared with the radar-AMeDAS precipitation. The model accurately expresses climate of Japan. In winter, observations reveal a lot of precipitation along the Japan Sea coast, and little precipitation along the Pacific Ocean coast. This characteristic is well reproduced by both runs. However, the precipitation of the ARCM run is somewhat overestimated. This wet bias is improved by the CRCM run. In western Japan, precipitation is large due to large-scale conditions, like the stationary front along Japan during the warm season. Neither run sufficiently reproduces the large amount of rain in western Japan. The CRCM run reproduces a smaller amount of rain than the ARCM run throughout the year, because of its cooler SST. Due to this, the CRCM run has somewhat lower scores than that of the ARCM run in the warm season.

In conclusion, the CRCM is an effective way to accurately reproduce the climate of Japan. Improvements on both the atmosphere and ocean models, will achieve a more accurate reproduction of the climate.

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